NASA TECHNICAL NOTE

NASA TN D-5758

c.1



NASA TN D-5758

# ROUND-TRIP TRAJECTORIES WITH STOPOVERS AT BOTH MARS AND VENUS

*by Edward A. Willis, Jr., and John A. Padrutt*

*Lewis Research Center*
*Cleveland, Ohio*

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1970

| | | |
|---|---|---|
| 1. Report No. NASA TN D-5758 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle ROUND-TRIP TRAJECTORIES WITH STOPOVERS AT BOTH MARS AND VENUS | | 5. Report Date April 1970 |
| | | 6. Performing Organization Code |
| 7. Author(s) Edward A. Willis, Jr., and John A. Padrutt | | 8. Performing Organization Report No. E-5291 |
| 9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135 | | 10. Work Unit No. 124-09 |
| | | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546 | | 13. Type of Report and Period Covered Technical Note |
| | | 14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract

Round-trip interplanetary trajectories that include stopovers at both Mars and Venus before the return to Earth are studied. Such trips fall roughly midway between conventional opposition- and conjunction-class Mars missions in terms of propulsive effort, trip time, and stay time. This trajectory mode appears to be of significant interest if Venus is considered to be an important eventual manned spaceflight goal.

| | |
|---|---|
| 17. Key Words (Suggested by Author(s)) Mars, Venus, Round trips, Stopovers, Trajectories | 18. Distribution Statement Unclassified - unlimited |

| | | | |
|---|---|---|---|
| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price* |
| Unclassified | Unclassified | 30 | $3.00 |

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

# ROUND-TRIP TRAJECTORIES WITH STOPOVERS AT BOTH MARS AND VENUS

by Edward A. Willis, Jr., and John A. Padrutt

Lewis Research Center

## SUMMARY

This report considers a class of efficient interplanetary round-trip trajectories that involve entering parking orbits at both Mars and Venus before returning to Earth. When the conventional two-body, impulsive-trajectory model is used, the following conclusions can be reached:

(1) Propulsive effort requirements and trip times for these trajectories fall roughly midway between those of conventional opposition- and conjunction-class trajectories to Mars only.

(2) Trajectories recur on a 6.4-year major cycle, and there are seven low-energy launch opportunities within that period. (Venus-swingby trajectories also recur on a 6.4-year cycle, and may be regarded as a special case of the trajectories considered herein.)

(3) Three of these seven opportunities are particularly desirable in that they involve optimum trip times of only about 700 days (as compared to 1000 days for conjunction-class trips to Mars or Venus only). This time may be reduced to 600 days without a major penalty in propulsive effort $\Sigma\Delta V$. Two other opportunities require an 890-day optimum trip time, but this may be reduced to about 750 days before a large penalty in $\Sigma\Delta V$ is incurred. The remaining two opportunities cannot be reduced much below 1000 days trip time.

(4) Optimum stay times at Mars tend to be short (e.g., 10 days) for short trip times, but can be increased to 50 or 75 days for a very minor $\Delta V$ increase. Optimum Venus stay times are generally longer than 75 days.

(5) Preliminary vehicle mass calculations, assuming representative payloads and typical stage parameters, suggest that the two-planet stopover mission will not be greatly heavier than a typical Mars mission and definitely lighter than the sum of two separate missions to Mars and Venus.

# INTRODUCTION

Manned missions to Mars and Venus may eventually become the prime focus of the national manned spaceflight program. Such missions clearly involve a new order of difficulty when compared to present orbital and lunar operations, and will depend on the proper functioning of systems which have yet to be developed. In order to define the requirements for these systems, it is now appropriate to evaluate preferred mission modes and trajectories.

Numerous studies have been made of manned missions to Mars or Venus that involve entering a capture orbit at the destination planet. Several of these single-planet stopover trajectories seem attractive on their own merits; nevertheless, it is not clear that two of them taken together comprise an optimum program for investigating both Mars and Venus. Therefore, this report analyzes an alternative class of trajectories, illustrated in figure 1, in which the space vehicle orbits both Venus and Mars before returning to Earth.

Previous stopover trajectory modes normally visited either Mars or Venus, but not both. The earliest studies involved the use of minimum-effort (Hohmann type) outbound and return trajectories, separated by a relatively long stay time at the destination planet. These conjunction-class trajectories yield very low propulsive effort $\Sigma\Delta V$ and Earth reentry speeds, but require stay times and trip times averaging 450 and 1000 days,

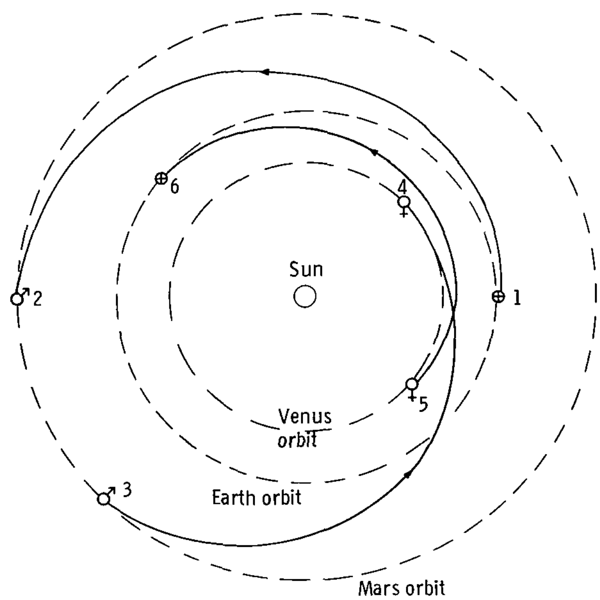



Figure 1. - Typical two-planet stopover trajectory. Earth-Mars-Venus-Earth, 1980.

respectively, for either planet (ref. 1). Higher energy trips to both planets have also been investigated extensively, and three categories of such "fast" trips have been reported: (1) opposition-class trajectories, (2) trajectories using one or two double-conic (three impulse) transfers, and (3) the Venus-swingby trajectory mode.

The conventional, opposition-class trip is discussed in references 2 to 4. For missions to Venus, this mode yields low velocity increments and reentry speeds for trip times averaging 450 to 550 days. For Mars missions, unfortunately, the $\Sigma\Delta V$'s and/or reentry speeds are quite high. As shown in references 5 and 6, these high $\Sigma\Delta V$'s and reentry speeds can be significantly lowered in many cases by employing a third impulse near perihelion of a long-angle transfer (fig. 2). These double-conic trajectories, in

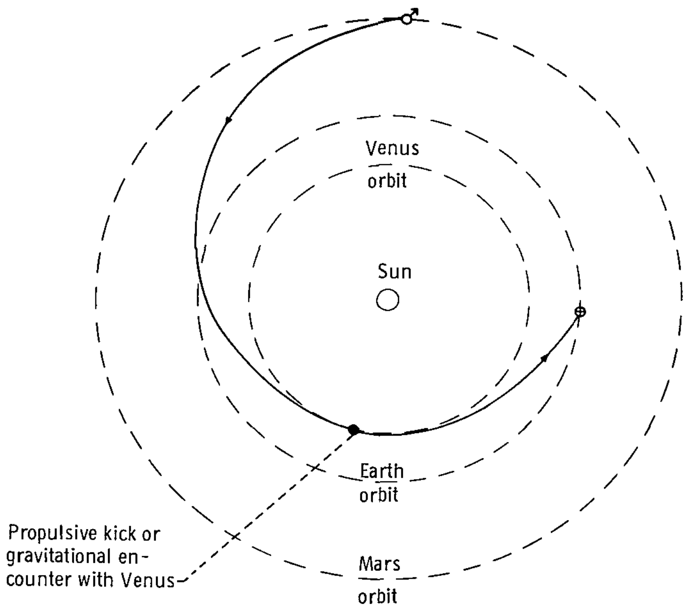



Figure 2. - Double-conic or Venus-swingby transfers.

addition, exhibit unusually wide launch windows for both Earth departure and Mars departure (refs. 6 and 7). Optimum trip times average 550 days.

Venus-swingby trajectories (fig. 2 and refs. 8 to 10) are similar to the double-conic trajectory in that the elements of a long-angle Earth-Mars or Mars-Earth transfer are modified in midcourse. The change, however, is supplied by Venus' gravity rather than by propulsion. The $\Sigma\Delta V$ requirements for these trajectories are somewhat variable but are generally below those of the double-conic type, and trip times are longer, 550 to 700 days.

The one element common to these trajectories is that only one planet is visited for any significant length of time. On the other hand, reference 11 indicates that both Mars and Venus are worthwhile objectives for manned investigations. There is no reason to assume that the optimum program for investigating both Mars and Venus would consist of running separate missions of the previously mentioned types. Accordingly, this report presents an initial, but relatively thorough, account of trajectories involving stopovers at both Mars and Venus. Numerical results are presented for launch opportunities from 1980 to 1999, trip times from 550 to 1100 days, and stay times at each planet ranging from 10 to several hundred days. These results are compared with those for the previously mentioned single-planet trajectory modes, and a sample mission application is discussed.

## INPUT ASSUMPTIONS

Many variables must be considered in evaluating final mission criteria, such as space vehicle mass or cost. Several useful mission parameters, however, can be studied on the basis of trajectory information alone, including

(1) Total propulsive effort (or total velocity increment) $\Sigma\Delta V$

(2) Total trip time $T_t$

(3) Stay times at the destination planets $T_s$

The mass ratio required for each propulsive maneuver is directly related to the associated velocity increment, and the sum of these increments is the best single indication of space vehicle mass that can be obtained without making detailed assumptions about the vehicle systems, payloads, and mission objectives. The velocity increment sum is therefore used as the primary criterion of merit for the purpose of developing and illustrating the present trajectory mode. It could be replaced by cost, mass, or other criteria without essentially changing the nature of the trajectories.

The trip time and stay times are treated as secondary criteria. A low value of $T_t$ would indicate a minimal exposure to the hazards of space, and the stay times limit the time available to accomplish the primary mission objectives.

The analysis is based on the well-known, impulsive, two-body trajectory model; that is, propulsive maneuvers are treated as impulses and the actual n-body problem is replaced by a sequence of two-body coasting arcs. Successive heliocentric arcs are joined by a midcourse impulse; that is, double-conic (three impulse) interplanetary transfers (ref. 6) are used whenever they yield a lower $\Sigma\Delta V$. Heliocentric and planetocentric arcs are related by matching conditions applied at the sphere of influence. Inside the sphere of influence, only the planet's gravitational field is considered; and outside, only the Sun's. The spheres of influence are taken to be of negligible size compared to interplanetary distances, but much larger than the parking-orbit dimensions. It is assumed that transfers begin and end in planetocentric parking orbits, and that the plane orbits are elliptic and coplanar. As reference 12 shows, the $\Sigma\Delta V$ penalty for using highly inclined, nearly $180^{o}$ transfers can be almost eliminated by using a broken-plane transfer with an optimum midcourse impulse. In fact, the true (i.e., optimum three dimensional) results are better approximated by the present two-dimensional calculation than by the more common three-dimensional, single-plane approach.

The following additional assumptions are used in computing numerical results:

(1) Atmospheric braking from $V_{AE} \leq 15.85$ kilometers per second (52 000 ft/sec) is used at Earth return. (Propulsive retrothrust is used if necessary to decrease $V_{AE}$ to this value.)

(2) Elliptic parking orbits ($e_{po} = 0.9$) are used at Mars and Venus (periapsides at 1.1 planet radii).

The planet orbit elements and physical data used herein are listed in table I. Tables II to IV give a sequence of Earth-Mars, Earth-Venus, and Venus-Mars alinement dates (from 1975 to 2000) that will prove useful in the following sections. These data were obtained from references 10 and 13.

# HOHMANN TRANSFERS FOR TWO-PLANET STOPOVERS

## Propulsive Effort

It is convenient initially to consider a simple special case that uses Hohmann-type (optimum travel time and travel angle) transfers between planets in circular orbits. Such a trip, illustrated in figure 1, can be easily analyzed, and the solutions provide a basis for understanding the general case presented later.

In this special case, it is well known that the minimum-energy interplanetary transfer trajectories are semiellipses with aphelion and perihelion tangent, respectively, to the outer and inner circular planetary orbits. The semimajor axes of these elliptical trajectories are thus

$$a_h = \frac{1}{2} (R_o + R_i) \tag{1}$$

where these and all following symbols are defined in the appendix. The travel time is

$$T_h = \frac{365.2568}{2} (a_h)^{3/2} \tag{2}$$

Noting that a heliocentric angle of 180° is traversed in these times, it may be seen that the necessary initial angular separation of the two planets involved is given by

$$\psi_{i,o} = 180^{o} - T_h \omega_o \tag{3}$$

$$\psi_{o,i} = \omega_i T_h - 180^{o} \tag{4}$$

(in degrees, measured in the direction of motion from the inner planet).

The heliocentric speeds upon arrival at the planetary orbits are

$$V_o = \sqrt{\left(\frac{2GM_{Sun}}{R_o + R_i}\right)\left(\frac{R_i}{R_o}\right)} \tag{5a}$$

$$V_i = \sqrt{\left(\frac{2GM_{Sun}}{R_i + R_o}\right)\left(\frac{R_o}{R_i}\right)} \tag{5b}$$

The planetocentric speeds are computed from

$$V_{\infty,o} = V_{planet} - V_o \tag{6a}$$

$$V_{\infty,i} = V_i - V_{planet} \tag{6b}$$

and propulsive velocity increments from

$$\Delta V = \left(V_{\infty}^2 + 2V_{cpo}^2\right)^{1/2} - V_{cpo}\left(1 + e_{po}\right)^{1/2} \tag{7}$$

The Hohmann travel times resulting from equation (2) are $(T_h)_{\oplus,♀} = 146.1$ days, $(T_h)_{\oplus,♂} = 258.9$, $(T_h)_{♂,♀} = 217.5$. Values resulting from equations (3) and (7) are given in tables V and VI.

## Trip Times, Stay Times, and Dates

The foregoing results may now be used to determine optimum departure and arrival dates at each terminal, and hence, the optimum trip times and stay times. Actual departure dates are computed by subtracting the appropriate Hohmann date taken from table V from the appropriate date listed in tables II, III, or IV

$$D_{dep} = D_{opp} - D_h \tag{8}$$

Arrival dates are then calculated by adding $T_h$ to equation (8)

$$D_{arr} = D_{dep} + T_h \tag{9}$$

This procedure results in six lists of departure and arrival dates for the Hohmann transfers, as presented in table VII.

The use of table VII is best illustrated by an example. Consider an Earth-Venus-Mars-Earth trip in 1980: the Earth departure and Venus arrival dates are found from table VII(a) to be 4318.2 and 4464.3, respectively. Comparing the latter with departure dates in table VII(d), it is seen that the next Venus-Mars transfer departure and arrival dates are 4638.9 and 4856.4, respectively. Comparing the arrival date to departures in table VII(f) shows the next Mars-Earth transfer departure date is 4897.1 and with a return to Earth on 5156.0. Thus, a total trip time of 837.8 days, including Mars and Venus stay times of 40.7 and 174.6 days, respectively, is predicted for this trip. Applying this same procedure to trips in other years leads to the results shown in table VIII.

## Trajectories with Reduced Trip Times

Although the trip times presented in table VIII may seem unreasonably long, it may be noted that this is due, in general, to an arrival date falling only slightly behind a departure date for the next leg. The stay time then approaches the synodic period for the two planets concerned. On the other hand, by departing about one synodic period earlier and using a slightly faster transfer, a large trip-time reduction is possible for only a small $\Sigma\Delta V$ penalty. For example, the 1982 Earth-Mars-Venus-Earth trip is reduced from 1283 to 710 days by deleting one Mars-Venus period from the Mars stay time, and one Venus-Earth period from the Venus stay time. Many cases of this nature are discussed later in the section GENERAL TWO-PLANET STOPOVERS.

## Recurrence Period

The synodic period between two planets, say Earth and Mars, is defined by

$$\tau_{\oplus,♂} = \frac{360^{\circ}}{\omega_{\oplus} - \omega_{♂}} = \frac{\tau_{\oplus}}{1 - \frac{\tau_{\oplus}}{\tau_{♂}}} \tag{10}$$

(Parameter values are given in table I.) By analogy, the "general synodic period" (i.e.. the recurrence period for Venus, Earth, and Mars alinements) is

$$T_{\oplus,♂;\,\oplus,♀} = \frac{\tau_{\oplus,♂}}{1 - \frac{\tau_{\oplus,♂}}{\tau_{\oplus,♀}}} \tag{11}$$

or approximately 2338 days (6.4 yr). During the course of one recurrence period, there are three Earth-Mars oppositions and four Earth-Venus conjunctions; the mutual planetary configurations at the end almost exactly duplicate those at the beginning. Consequently, the two-planet stopover trajectories recur periodically whether they are minimum-energy or time-constrained. Additional cases may then be determined by adding whole multiples of 2338 days to each baseline arrival and departure date. The recurrence phenomenon for Venus-swingby Mars trips (discussed in ref. 10, under the terminology "syzygistic" period) involves the same 2338-day period.

## Comparison with Venus-Swingby Trajectories

Two-planet stopovers and Venus-swingby trajectories are similar in that the same planets and recurrence relations are involved. The former, however, are a more general class since they present several additional degrees of freedom that cannot be freely chosen in a swingby. These include the stay time, parking orbit elements, and propulsive maneuvers at Venus. The stay time primarily determines the degree of physical resemblance that can exist between these two modes. Clearly, the smallest possible discrepancy in any one encounter date is equal to half the Venus stay time. If long stay times are optimum (or required by groundrules), there can be little, if any, physical similarity.

Short-stay missions, however, can closely resemble their swingby counterparts, at least in the sense that trajectory legs occur in the same order and involve similar (within plus or minus the stay time) encounter dates. Cases where this is true will be presented later. On the other hand, it should be recognized that the procedure of estimating a double-stopover trip by inserting a brief Venus stopover into a swingby is likely to yield unrealistically high $\Sigma\Delta V$'s unless followed by a thorough optimization. This is because swingbys with low $\Sigma\Delta V$'s often have high passage speeds at Venus and hence (when converted to double stopovers) high $\Delta V$'s at Venus.

## GENERAL TWO-PLANET STOPOVERS

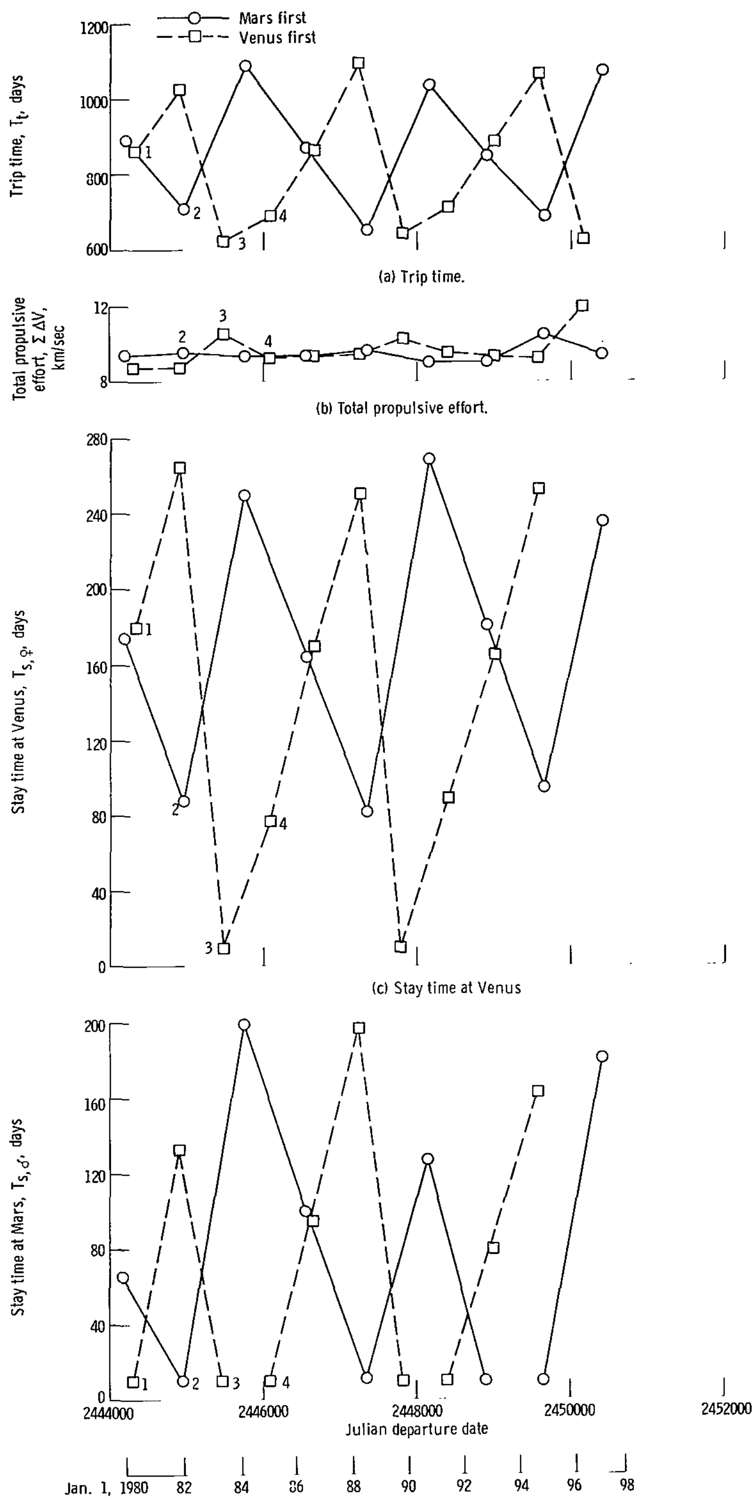
The dates, travel times, and stay times estimated as described in the preceding section were used for initial guesses in the trajectory computer code of reference 6. This code involves elliptic coplanar planet orbits, whereas circular orbits were assumed so far. It uses optimum three-impulse (double conic) transfers whenever applicable, and searches for the optimum values of the departure and arrival dates, stay and travel times, and other adjustable parameters.

### Characteristics of Mars-Venus Stopover Trajectories

Stay times at Mars and Venus were optimized subject to an allowable minimum stay of 10 days at each planet. Thus, the results to be presented below are based on a total planetary stay time of at least 20 days (although, in most cases, longer times are obtained).

Low-energy trajectories. - The first concern of this section is to validate the Hohmann-transfer predictions of minimum $\Sigma\Delta V$'s and optimum trip and stay times. Table IX first presents the seven Hohmann-class trips for one recurrence period. These are the same trips as were discussed in connection with table VIII, except that elliptic planet orbits and minor adjustments in travel and stay times and dates are incorporated as required for more realistic optimization. By noting the fairly close agreement between the table VIII and IX results, it may be inferred that the previously discussed approximate method using Hohmann transfers is a reliable way to predict the possible dates for low-energy trips.

As previously explained, it is often possible to reduce the long trip times shown in table IX rather dramatically, by deducting an appropriate synodic period from one of the stay times. It was anticipated that by properly reoptimizing the trajectory, a second local minimum could be found at a lower trip time and for little penalty in $\Sigma\Delta V$. This proved to be the case for three of the seven opportunities in one 6.4-year recurrence period. The results are presented in figure 3, where trip time, $\Sigma\Delta V$, Venus stay time,




(d) Stay time at Mars.

Figure 3. - Characteristics of two-planet stopover trajectories. Optimum trip time and stay time.

and Mars stay time are all plotted as functions of launch year from 1980 to 1998. The 6.4-year periodicity of the results is clearly evident.

Consider first the trip time and $\Sigma\Delta V$ behavior (figs. 3(a) and (b)). The three originally longest trajectories were the ones that responded to the reduction process (i.e., they attained new local minimums). The resulting $\Sigma\Delta V$'s are, as hoped, only slightly higher than those of the long-trip-time minimums. These trajectories may, in fact, be the better approximation to mass-optimized trajectories because of the effect of trip time upon life-support systems. Details are presented in the lower block of table IX.

It is evident that by choosing the most appropriate trajectory profile (e.g., Mars first in 1982), it is possible to obtain low-energy trips with trip times of 620 to 700 days in 1982, 1983, 1985, and the 6.4-year repeats of these trips. In 1980 (and its repeats), both profiles require about 850 days, and it appears to be more difficult to obtain short trip times in that period; however, the $\Sigma\Delta V$ is still quite low. The sequence marked 1-2-3-4 on figures 3(a) and (b) represents the most attractive two-planet stopover trajectories in terms of $\Sigma\Delta V$ and trip time discussed up to this point, and is referred to hereinafter as the "minimum-energy family."

The stay times associated with the preceding trajectories are presented in figures 3(c) and (d). Again the sequence 1-2-3-4 denotes the minimum-energy family. It is evident that this family tends to have short stay times at Mars and this could be an undesirable feature, depending on mission objectivies.

Effect of time constraints. - Three of four trips in the minimum-energy family

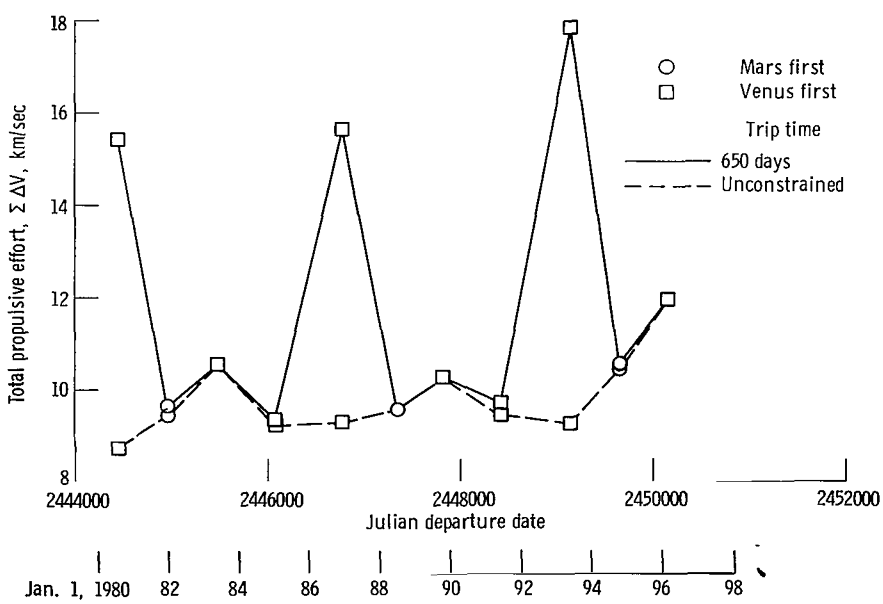



Figure 4. - Two-planet stopover trajectories, with total trip times of 650 days and unconstrained.

involve trip times of less than 2 years and even the exception (1980) is shorter than a Hohmann or conjunction-class trip to Mars only (which typically requires 1000 days). It may nevertheless be desirable to impose a shorter trip-time limitation or longer stay times, even if this involves some $\Sigma\Delta V$ penalty. The effect of constraining $T_t$ to 650 days or less is shown in figure 4. The constraint is binding in all periods but 1983, but has a major effect only in 1980 where $\Sigma\Delta V$ is increased from 8.7 to 15.4 kilometers per second, a penalty of about 80 percent.

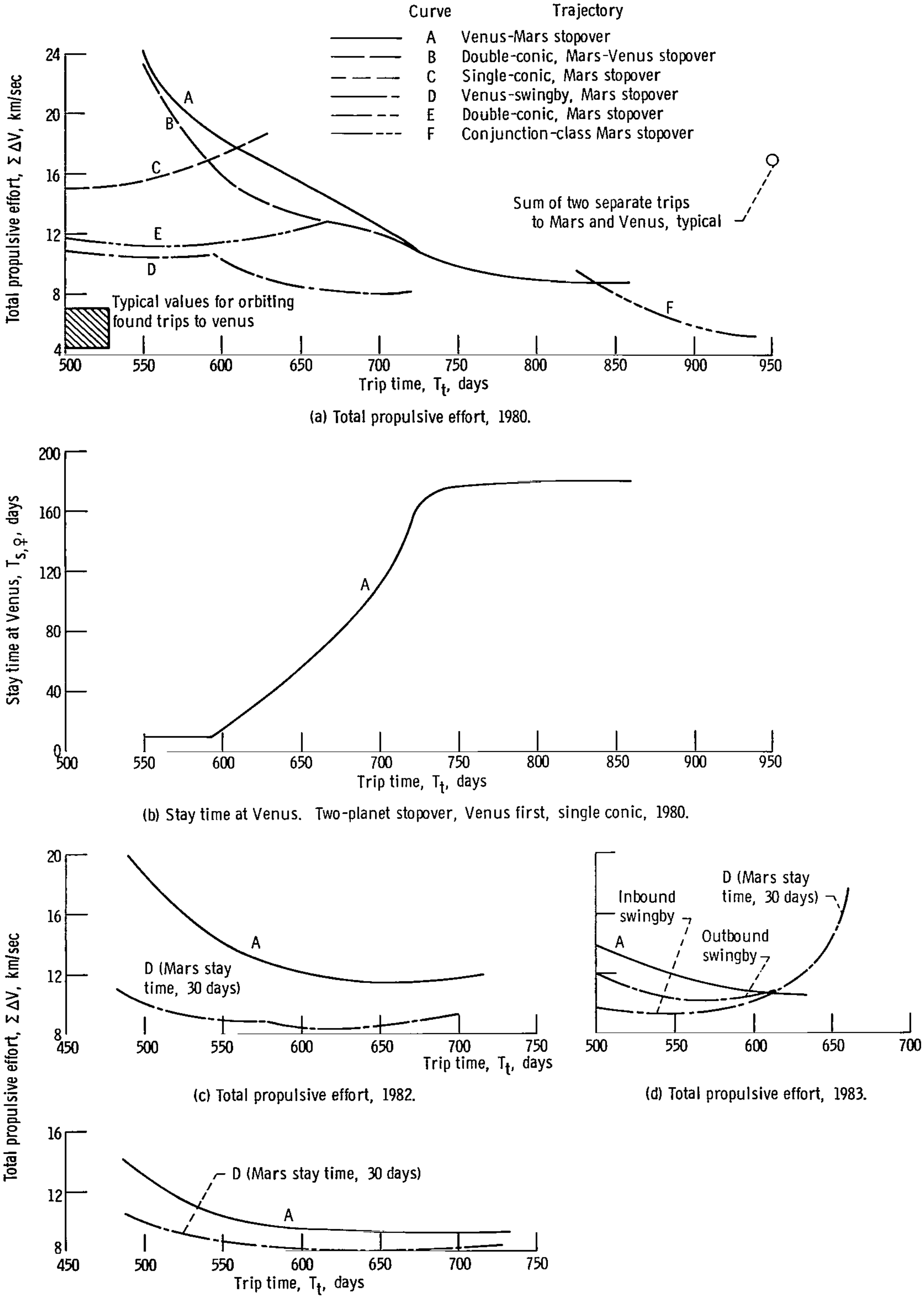
The effect of $T_t$ on $\Sigma\Delta V$ and $T_s$ in the difficult 1980 period is considered in more detail in figures 5(a) and (b). In figure 5(a), consider only curve A, which represents the present two-planet stopover trajectories. The other curves represent different trajectory options and need not be considered now. Note there is a mild "knee" at about 720 days where $\Sigma\Delta V$ increases quickly for shorter times. Stay times vary slowly at long trip times but decrease rapidly below 720 days - especially at Venus (fig. 5(b)).

Planetary configurations in 1980 are such that $T_t$ reductions occur primarily by decreasing the Venus stay time; for example, in decreasing $T_t$ from 750 to 650 days, $T_s$ is shortened from 177 to 68 days, while Earth-Venus travel time and other parameters vary relatively slowly. Thus as $T_t$ decreased, the Earth-departure and Venus-arrival dates were delayed by about the same amount.

This means that the Earth-Venus travel angle $\omega_{♀} - \omega_{\oplus}$ increases by about 0.7 degree per day, or roughly $10^{\circ}$ for each 2-week reduction in $T_t$. The resulting larger-than-optimum travel angles involve significant $\Sigma\Delta V$ penalties which can be partly offset by the use of a double-conic transfer (ref. 6). This is shown by curve B in figure 5(a); the maximum saving is 2.5 out of 17 kilometers per second, or 15 percent, and occurs for 620 days trip time.

The solid curves in figures 5(c) to (e) show the effect of $T_t$ on $\Delta V$ for other members of the minimum-energy family. Clearly, the trip times may be reduced to 600 days or perhaps a bit less in these three different periods without incurring major $\Sigma\Delta V$ penalties.

Previous results show that optimum stay times at Mars tend to be short, and this may be a disadvantage. The effect of constraining stay time at Mars is shown in figure 6 for a 750-day (fixed) trip in 1980. Actually, the Mars stay time can be increased to 60 to 75 days for a very minor penalty in $\Sigma\Delta V$. This may be an important consideration, depending on the relative emphasis placed on Mars-related and Venus-related mission objectives.




(a) Total propulsive effort, 1980.

(b) Stay time at Venus. Two-planet stopover, Venus first, single conic, 1980.

(c) Total propulsive effort, 1982.

(d) Total propulsive effort, 1983.

(e) Total propulsive effort, 1985.

Figure 5. - Effect of trip time on one- and two-planet stopover trajectories to Mars.

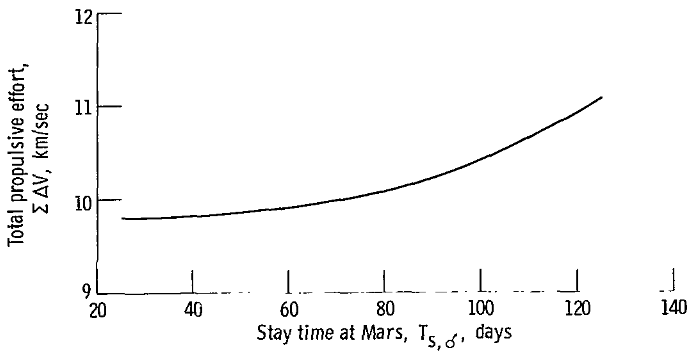



Figure 6. - Effect of Mars stay time constraint. Total trip time, 750 days. 1980.

## Comparison of Trajectory Modes

Although the Mars-Venus stopover mission is novel and interesting in its own right, it must compete with better-known profiles if it is to find application in the manned space-flight program. In this section, the previously discussed characteristics of Mars-Venus stopover trajectories are compared with corresponding results for conventional opposition-class, double-conic opposition-class, Venus-swingby, and conjunction-class trajectories to Mars.

Propulsive effort and and trip times. - Figure 5(a) portrays the $\Sigma\Delta V$-against-$T_t$ behavior of the four abovementioned trajectory modes, again for the 1980 opportunity. The two-planet results are indicated by curves A and B and were previously discussed. Note that $\Sigma\Delta V$'s comparable to those of a conventional opposition-class mission (curve C) can be obtained for trip times of 600 days or more. Using double-conic, opposition-class trajectories for comparison (curve E), the present trajectories yield comparable $\Sigma\Delta V$'s at about 700 days trip time, and are superior at longer times. For Venus-swingby trajectories (curve D), the minimum $\Sigma\Delta V$ occurs at about 700 days; at this value of $T_t$, the two-planet mode involves about a 4-kilometer-per-second $\Sigma\Delta V$ penalty. In general, the Venus-swingby mode offers an attractive compromise between $T_t$ and $\Sigma\Delta V$, and appears to be the major alternative to which the present trajectories should be compared. If the trip time can be extended to about 800 days, the penalty is under 1 kilometer per second. At trip times greater than about 850 days, the conjunction-class trips (curve F) yield the lowest $\Sigma\Delta V$, and this advantage increases to 4 kilometers per second at trip times in the 950 to 1000 days range.

In 1980, the two-planet stopover does not require greatly increased $\Sigma\Delta V$ compared to the swingby mode for trip times beyond 750 days. It should be recalled, moreover, that the 1980 opportunity proved particularly difficult for Mars-Venus stopover trajectories, from the viewpoint of obtaining relatively short trip times. The more representative opportunities of 1982, 1983, and 1985 are therefore shown in figures 5(c) to (e).

The Mars-Venus stopovers are shown by the solid curves (A), while Venus swingbys are indicated by the dash-dot curves (D). (The other three modes are not further discussed.) In 1982 to 1985, the two profiles are more competitive at trip times of about 600 days, with the swingby being progressively better at shorter trip times and the Mars-Venus stopover being highly competitive or somewhat superior at longer times. As in 1980, the conjunction-class trip (not illustrated in figs. 5(c) to (e)) would yield the lowest $\Sigma\Delta V$ for trip times greater than 850 or 900 days. Thus, in 1982 to 1985 the two-planet trajectory mode is competitive over a considerable range of trip times, 600 to 850 days.

Mission objectives capability. - If $\Sigma\Delta V$ and trip time were the only considerations, there would be little need for the two-planet class of trajectories. Existing Mars trajectory modes generally yield shorter trip times for comparable $\Sigma\Delta V$'s or lower total $\Sigma\Delta V$'S at comparable trip times. Moreover, trajectories to Venus alone can be performed for $\Sigma\Delta V$'s of the order of only 7 to 8 kilometers per second for trip times of 400 to 550 days (ref. 4).

On the other hand, the Mars mission comparisons do not recognize the fact that Venus may also be a legitimate object for scientific and technical investigations. Although a manned landing on Venus is not presently contemplated, there are several major objectives (e.g., preparation of a detailed radar map of the entire Venusian surface or remote manipulation of a mobile soft-landed probe) which would either require, or benefit significantly from, the presence of a properly trained crew in orbit.

Thus, it seems that the two-planet mode could more appropriately be compared with the sum of individual Mars and Venus round trips. This sum typically is as shown by the circular symbol at the upper right of figure 5(a). On this basis the Mars-Venus stopover is clearly superior to any combination of Mars-only and Venus-only round trips.

Vehicle mass. - Although a comprehensive initial-mass survey is beyond the scope of this report, it is of some interest to demonstrate that the previously described features carry over, for typical mission examples, when initial mass in Earth orbit (IMEO) is used as a criterion of merit. Therefore, mission calculations were performed for the four trajectories in the minimum energy family, in the 1980 to 1986 recurrence period. The results are compared with those for the four most nearly comparable Venus-swingby trajectories in the same period. In each case, scalable ("rubber") solid-core nuclear stages are assumed, one for Earth escape and one for capture and escape at each planet. The Earth-escape stage consists of one engine system and one set of tankage. The destination-planet stages each consist of one restartable engine system and two tankage sets; the first is jettisoned after capture, and the second is jettisoned along with the engine system after escape. The stage and payload input values used are listed in table X. The payloads were taken from previous mission reports (refs. 14 and 15). The stage inputs, though arbitrary, are representative. (Earth atmospheric braking and highly elliptic parking orbits are used.)

The resulting minimum IMEO's and associated optimum trip times for both trajectory modes are presented in table XI, and pertinent trajectory details are presented in table XII. From the data in table XI it is clear that the present double-stopover trajectory mode generally involves IMEO and trip-time penalties of around 20 percent, as might be anticipated from the $\Sigma\Delta V$ results. The mass penalty ranges from 45 000 to 138 000 kilograms; these values might be compared with an IMEO of about 300 000 kilograms found in reference 15 for a manned Venus orbiter mission with assumptions similar to the present ones. The trip-time penalty varies from 77 to 204 days; again, these might be compared with the 460 to 565 days optimum trip time found in reference 15 for missions to Venus only.

These comparisons indicate that the value of the two-planet stopover trajectory

Maneuver dates. - It is of some interest to compare the maneuver dates shown in table XII for the double-stopover and swingby missions. As was predicted earlier, there is no evident similarity when the double stopover involves a long stay time at Venus. For short-stay missions, however, the dates are more nearly equal (i.e., within plus or minus the Venus stay time), and there is a definite qualitative resemblance between the trajectories (the 1983 Venus-Mars double stopover is closely comparable with one of the 1984 outbound swingbys found in ref. 10).

The comparisons above indicate that the value of the two-planet stopover trajectory mode will depend on whether Venus, in addition to Mars, is considered an important manned spaceflight goal. If it is not, the present trajectories are of no interest. If it is, the present trajectories offer a total IMEO saving in the 150 000- to 250 000-kilogram range, and total trip-time savings on the order of 250 to 400 days. They also imply further cost savings (not evaluated herein) by halving the requirement for astronaut crews and expensive subsystems such as the command module. The primary disadvantage is that the trip times applicable to one crew are longer than would seem desirable.

## CONCLUDING REMARKS

In this report, a class of round-trip trajectories with stopovers at both Mars and Venus has been studied. By contrast, previously studied trajectory modes usually include a stopover at only one planet, not both. Thus, if it is accepted that Venus is a legitimate goal for manned reconnaissance, the present trajectory mode offers the potential of essentially doubling the "return" derived from a single manned spaceflight mission.

The two-planet stopovers were evaluated by computer simulation. Assuming elliptic planetary parking orbits and atmospheric braking at Earth, the following conclusions were obtained:

1. Total velocity increment $\Sigma\Delta V$ requirements for two-planet stopovers are moderate and are not greatly higher than those of the best existing trajectory modes for trips to Mars only.

2. There are seven low-energy launch opportunities within each 6.4-year repeating period. Of these, three involve only moderate (<2 yr) trip times, two require very long (>3 yr) times, and two require an intermediate time of about $2\frac{1}{2}$ years. Four of the seven visit Venus first and Mars second, while the order is reversed for the remaining three.

3. The trip times associated with the three most desirable trips in each repeating period can be decreased from the optimum values of 650 to 700 days to as little as 600 days without incurring prohibitive $\Sigma\Delta V$ penalties.

4. Stay times tend to be short (e.g., 10 days) especially at Mars, but can be lengthened to about 60 days without major $\Sigma\Delta V$ penalty.

5. For typical nuclear stage inputs, it would appear that the Mars-Venus two-planet stopover trajectories yield initial vehicle weights which are somewhat (e.g., 20 percent) larger than those of either the Venus-swingby trip to Mars or the Venus orbiter trip, but significantly less than the sum of these two.

From the foregoing it may be also concluded that, if Venus as well as Mars is a major manned spaceflight goal, the present class of trajectories is of legitimate interest and should be taken into account in future mission studies. In particular, vehicle mass studies for the two-planet trajectories should be performed for a wider range of flight system inputs and payloads; any further results should be optimized on a mass, cost, or reliability basis rather than $\Sigma\Delta V$; and a rationale must be established for comparing the present trajectories with those for stopovers at only one planet.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 18, 1969,
124-09.

# APPENDIX - SYMBOLS

| | |
|---|---|
| $A_o$ | initial acceleration |
| $a$ | semimajor axis of elliptical heliocentric trajectory, AU |
| $D_{arr}$ | Julian arrival date |
| $D_{dep}$ | Julian departure date |
| $D_h$ | Julian departure date for a Hohmann transfer, measured relative to opposition |
| $D_{opp}$ | Julian date of planetary opposition |
| EMOS | Earth mean orbital speed, 29.77 km/sec |
| $e_{po}$ | eccentricity of parking orbit about planet |
| $F$ | engine thrust |
| $GM_{Sun}$ | gravitational parameter of Sun |
| $g_{\oplus}$ | gravitational acceleration at Earth's surface, 9.80665 m/sec |
| $I_{sp}$ | specific impulse, sec |
| $M_{ac}$ | after-cooling propellant mass |
| $M_{aux}$ | auxiliary equipment mass |
| $M_e$ | engine mass |
| $M_{fs}$ | thrust sensitive structure mass |
| $M_g$ | vehicle gross mass |
| $M_{is}$ | interstage mass |
| $M_p$ | propellant mass |
| $M_{pay}$ | payload mass |
| $M_{ps}$ | propellant sensitive structure mass |
| $R$ | radius of planet's orbit, AU |
| $T$ | syzygistic period |
| $T_h$ | Hohmann transfer time |
| $T_{s,♂}$ | stay time at Mars |
| $T_{s,♀}$ | stay time at Venus |
| $T_t$ | total trip time |

$V_{AE}$ upper limit for nonpropulsive Earth reentry

$V_{cpo}$ circular velocity about planet at altitude of 0.1 times radius of planet

$V_i$ heliocentric velocity upon arrival at orbit of inner planet

$V_o$ heliocentric velocity upon arrival at orbit of outer planet

$V_{planet}$ mean orbital speed of planet

$V_\infty$ planetocentric approach speed

$\Delta V$ single velocity increment

$\tau_a$ sidereal period of planet a

$\tau_{a,b}$ synodic period of planet a with respect to planet b

$\psi_{a,b}$ initial angular separation required for going from planet a to planet b by means of a Hohmann transfer; measured positively from inner planet

$\omega$ planetary mean angular motion about Sun

Subscripts:

h Hohmann transfer

i inner planet

max maximum

o outer planet

$\oplus$ Earth

♂ Mars

♀ Venus

# REFERENCES


1. Taylor, James J.; and Wilson, Sam W., Jr.: A Minimum-Energy Mission Plan for the Manned Exploration of Mars. NASA TN D-5502, 1969.
2. Himmel, S. C.; Dugan, J. F., Jr.; Luidens, R. W.; and Weber, R. J.: A Study of Manned Nuclear-Rocket Missions to Mars. Aerospace Eng., vol. 20, no. 7, July 1961, pp. 18-19, 51-58.
3. Knip, Gerald, Jr.; and Zola, Charles L.: Three-Dimensional Trajectory Analysis for Round-Trip Missions to Mars. NASA TN D-1316, 1962.
4. Zola, Charles L.; and Knip, Gerald, Jr.: Three-Dimensional Trajectory Analysis for Round-Trip Missions to Venus. NASA TN D-1319, 1962.
5. Willis, Edward A., Jr.: New Class of Optimal Interplanetary Trajectories with Specified Trip Time. Paper 65-66, AIAA, Jan. 1965.
6. Willis, Edward A., Jr.: Optimization of Double-Conic Interplanetary Trajectories. NASA TN D-3184, 1966.
7. Doll, John R.: Earth-Orbit Masses for Five-Impulse Mars Stopover Missions in 1980. J. Spacecraft Rockets, vol. 5, no. 5, May 1968, pp. 517-521.
8. Sohn, Robert L.: Venus Swingby Mode for Manned Mars Missions. J. Spacecraft Rockets, vol. 1, no. 5, Sept.-Oct. 1964, pp. 565-567.
9. Deerwester, Jerry M.: Initial Mass Savings Associated with the Venus Swingby Mode of Mars Round Trips. Paper 65-89, AIAA, Jan. 1965.
10. Anon.: Planetary Flight Handbook. Part 6: Mars Stopover Mission Using Venus Swingbys. NASA SP-35, pt. 6, 1968.
11. Anon.: Space Research-Direction for the Future. Report by the Space Science Board (H. H. Hess, Chairman), Woods Hole, Mass., 1965.
12. Fimple, W. R.: Optimum Midcourse Plane Changes for Ballistic Interplanetary Trajectories. AIAA J., vol. 1, no. 2, Feb. 1963, pp. 430-434.
13. Eshleman, Von R.: Radar Astronomy. Science, vol. 158, no. 3801, Nov. 3, 1967, pp. 585-597.
14. Luidens, Roger W.; et al.: Manned Mars Landing Mission by Means of High-Thrust Rockets. NASA TN D-3181, 1966.
15. Willis, Edward A., Jr.: Manned Venus Orbiting Mission. NASA TM X-52311, 1967.
16. Willis, Edward A., Jr.: Finite-Thrust Escape From and Capture Into Circular and Elliptic Orbits. NASA TN D-3606, 1966.

TABLE I. - PLANET ORBIT ELEMENTS AND PHYSICAL DATA

| | Venus | Earth | Mars |
|---|---|---|---|
| Semimajor axis, AU[a] | 0.723 332 | 1.000 000 | 1.523 691 |
| Eccentricity | 0.006 793 | 0.016 726 | 0.093 368 |
| Inclination to ecliptic, deg[b] | 3.394 23 | 0.0 | 1.849 91 |
| Mean longitude of ascending node, deg | 76.319 72 | --------- | 49.249 03 |
| Mean longitude of perihelion, deg | 131.008 31 | 102.252 53 | 335.322 69 |
| Mean longitude at epoch[c], deg | 174.294 31 | 100.158 15 | 258.767 29 |
| Position of vernal equinox, deg | -102.27 | 0.0 | -67.01 |
| Mean motion, deg/day | 1.602 131 | 0.985 609 | 0.524 033 |
| Sidereal period, days | 224.701 | 365.256 | 686.98 |
| Synodic period, days | 583.92 | ---------- | 779.94 |
| Mean orbital speed, km/sec | 34.999 | 29.766 | 24.113 |
| Inclination of equator to orbit plane, deg | 3 | 23.450 | 23.984 |
| Gravitational parameter[d], $km^3/sec^2$ | $3.1993\times10^5$ | $3.9857\times10^5$ | $0.4088\times10^5$ |
| Planetary radius, km | 6100 | 6378 | 3415 |
| Parking orbit radius in terms of planet radius | 1.1 R | 1.1 R | 1.1 R |
| Circular velocity at parking orbit periapse radius, km/sec | 6.9050 | 7.5373 | 3.2989 |
| Parking orbit eccentricity, $e_{po}$ | 0.9 | 0.0 | 0.9 |

[a] 1 AU = 149 599 000 km

[b] Zero inclination used in calculations.

[c] Epoch = 1.5 Jan. 1960 eastern standard time (2436935.0 Julian).

[d] $GM_{Sun} = 1.327155\times10^{11}\ km^3/sec^2$.

TABLE II. - OPPOSITIONS OF MARS,

1975 TO 1999

| Julian date | Calendar date | Heliocentric longitude, deg |
|---|---|---|
| 2442762.1 | 15.6 Dec. 1975 | 82.75 |
| 2443530.5 | 22.0 Jan. 1978 | 121.35 |
| 2444294.7 | 25.2 Feb. 1980 | 155.48 |
| 2445059.9 | 31.4 Mar. 1982 | 190.03 |
| 2445831.9 | 11.4 May 1984 | 230.50 |
| 2446621.8 | 10.3 July 1986 | 287.37 |
| 2447432.7 | 28.2 Sept. 1988 | 4.92 |
| 2448223.3 | 27.8 Nov. 1990 | 64.90 |
| 2448995.4 | 7.9 Jan. 1993 | 107.15 |
| 2449760.5 | 12.0 Feb. 1995 | 142.35 |
| 2450524.8 | 17.3 Mar. 1997 | 176.20 |
| 2451293.2 | 24.7 Apr. 1999 | 213.51 |

TABLE III. - INFERIOR CONJUNCTIONS

OF VENUS, 1975 TO 1999

| Julian date | Calendar date | Heliocentric longitude, deg |
|---|---|---|
| 2442652.0 | 27.5 Aug. 1975 | 333.42 |
| 2443239.8 | 6.3 Apr. 1977 | 196.11 |
| 2443820.4 | 7.9 Nov. 1978 | 44.85 |
| 2444405.8 | 15.3 June 1980 | 264.05 |
| 2444990.9 | 21.4 Jan. 1982 | 120.75 |
| 2445571.7 | 25.2 Aug. 1983 | 331.09 |
| 2446159.4 | 3.9 Apr. 1985 | 193.73 |
| 2446739.9 | 5.4 Nov. 1986 | 42.33 |
| 2447325.5 | 13.0 June 1988 | 261.79 |
| 2447910.4 | 18.9 Jan. 1990 | 118.18 |
| 2448491.3 | 22.8 Aug. 1991 | 328.77 |
| 2449079.0 | 1.5 Apr. 1993 | 191.35 |
| 2449659.5 | 3.0 Nov. 1994 | 39.80 |
| 2450245.2 | 10.7 June 1996 | 259.52 |
| 2450830.0 | 16.5 Jan. 1998 | 115.60 |
| 2451411.0 | 20.5 Aug. 1999 | 326.46 |

TABLE IV. - MARS-VENUS

ALINEMENTS, 1975 TO 1999

| Julian date | Calendar date | Heliocentric longitude, deg |
|---|---|---|
| 2442700.1 | 14.6 Oct. 1975 | 49.97 |
| 2443016.2 | 25.7 Aug. 1976 | 197.90 |
| 2443367.1 | 11.6 Aug. 1977 | 38.68 |
| 2443685.2 | 25.7 June 1978 | 189.71 |
| 2444033.8 | 9.3 June 1979 | 26.79 |
| 2444354.4 | 24.9 Apr. 1980 | 181.71 |
| 2444700.1 | 5.6 Apr. 1981 | 14.32 |
| 2445023.6 | 23.1 Feb. 1982 | 173.84 |
| 2445366.0 | 31.5 Jan. 1983 | 1.32 |
| 2445692.9 | 24.4 Dec. 1983 | 166.08 |
| 2446031.7 | 27.2 Nov. 1984 | 347.93 |
| 2446362.3 | 23.8 Oct. 1985 | 158.37 |
| 2446697.2 | 23.7 Sept. 1986 | 334.33 |
| 2447031.6 | 24.1 Aug. 1987 | 150.68 |
| 2447362.7 | 20.2 July 1988 | 320.72 |
| 2447701.0 | 23.5 June 1989 | 142.97 |
| 2448028.4 | 16.9 May 1990 | 307.33 |
| 2448370.3 | 23.8 Apr. 1991 | 135.19 |
| 2448694.3 | 12.8 Mar. 1992 | 294.34 |
| 2449039.6 | 21.1 Feb. 1993 | 127.31 |
| 2449360.5 | 8.0 Jan. 1994 | 281.87 |
| 2449708.7 | 22.2 Dec. 1994 | 119.28 |
| 2450027.1 | 5.6 Nov. 1995 | 270.00 |
| 2450377.8 | 21.3 Oct. 1996 | 111.06 |
| 2450694.1 | 2.6 Sept. 1997 | 258.73 |
| 2451046.7 | 21.2 Aug. 1998 | 102.60 |
| 2451361.4 | 1.9 July 1999 | 248.05 |

TABLE VI. - VELOCITY INCREMENTS FOR

HOHMANN TRANSFERS

| Departure planet | Destination planet | Propulsive effort, ΔV, km/sec | | Total propulsive effort, Σ ΔV, km/sec |
|---|---|---|---|---|
| | | Departure | Arrival | |
| Mars-first trip | | | | |
| Earth | Mars | 3.521 | 0.817 | 4.338 |
| Mars | Venus | 2.122 | 1.819 | 3.941 |
| Venus | Earth | .615 | (a) | .615 |
| | | | | 8.894 |
| Venus-first trip | | | | |
| Earth | Venus | 3.410 | 0.615 | 4.025 |
| Venus | Mars | 1.819 | 2.122 | 3.941 |
| Mars | Earth | .817 | (a) | .817 |
| | | | | 8.783 |

[a]Atmospheric braking used at Earth return.

TABLE V. - INITIAL CONFIGURATION ANGLES FOR HOHMANN TRANSFERS, AND CORRESPONDING DATES (RELATIVE TO OPPOSITION)

| Departure planet | Destination planet | | |
|---|---|---|---|
| | Venus | Earth | Mars |
| Configuration angle, deg | | | |
| Venus | ----- | 36.0 | 66.0 |
| Earth | 54.0 | ---- | 44.3 |
| Mars | 168.4 | 75.1 | ---- |
| Dates of occurrence (days before opposition) | | | |
| Venus | ----- | 58.4 | 61.2 |
| Earth | 87.6 | ----- | 96.0 |
| Mars | 156.2 | 162.8 | ---- |

TABLE VII. - DATES FOR HOHMANN TRANSFERS BETWEEN VENUS, EARTH, AND MARS

(a) Earth-Venus transfer

| Opposition calendar year | Departure date (Julian date minus $2.44\times10^6$) | Arrival date (Julian date minus $2.44\times10^6$) |
|---|---|---|
| 1980 | 4318.2 | 4464.3 |
| 1982 | 4903.3 | 5049.4 |
| 1983 | 5484.1 | 5630.2 |
| 1985 | 6071.8 | 6217.9 |
| 1986 | 6652.3 | 6798.4 |
| 1988 | 7237.9 | 7384.0 |
| 1990 | 7822.8 | 7968.9 |
| 1991 | 8403.7 | 8549.8 |
| 1993 | 8991.4 | 9137.5 |
| 1994 | 9571.9 | 9718.0 |
| 1996 | 10157.6 | 10303.7 |
| 1998 | 10742.4 | 10888.5 |
| 1999 | 11323.4 | 11469.5 |

(b) Earth-Mars transfer

| Opposition calendar year | Departure date (Julian date minus $2.44\times10^6$) | Arrival date (Julian date minus $2.44\times10^6$) |
|---|---|---|
| 1980 | 4198.6 | 4457.5 |
| 1982 | 4963.8 | 5222.7 |
| 1984 | 5735.8 | 5994.7 |
| 1986 | 6525.7 | 6784.6 |
| 1988 | 7336.6 | 7595.5 |
| 1990 | 8127.2 | 8386.1 |
| 1993 | 8899.3 | 9158.2 |
| 1995 | 9664.4 | 9923.3 |
| 1997 | 10428.7 | 10687.6 |
| 1999 | 11197.1 | 11456.0 |

(c) Mars-Venus transfer

| Opposition calendar year | Departure date (Julian date minus $2.44\times10^6$) | Arrival date (Julian date minus $2.44\times10^6$) |
|---|---|---|
| 1979 | 3877.6 | 4095.1 |
| 1980 | 4198.2 | 4415.7 |
| 1981 | 4543.9 | 4761.4 |
| 1982 | 4867.4 | 5084.9 |
| 1983 | 5209.8 | 5427.3 |
| 1983 | 5536.7 | 5754.2 |
| 1984 | 5878.5 | 6096.0 |
| 1985 | 6206.1 | 6423.6 |
| 1986 | 6541.0 | 6758.5 |
| 1987 | 6875.4 | 7029.9 |
| 1988 | 7206.5 | 7424.0 |
| 1989 | 7544.8 | 7762.3 |
| 1990 | 7872.2 | 8089.7 |
| 1991 | 8214.1 | 8431.6 |
| 1992 | 8538.1 | 8755.6 |
| 1993 | 8883.4 | 9100.9 |
| 1994 | 9204.3 | 9421.8 |
| 1994 | 9552.5 | 9770.0 |
| 1995 | 9870.9 | 10088.4 |
| 1996 | 10221.6 | 10439.1 |
| 1997 | 10537.9 | 10755.4 |
| 1998 | 10890.5 | 11108.0 |
| 1999 | 11205.2 | 11422.7 |

(d) Venus-Mars transfer

| Opposition calendar year | Departure date (Julian date minus $2.44\times10^6$) | Arrival date (Julian date minus $2.44\times10^6$) |
|---|---|---|
| 1979 | 3972.6 | 4190.1 |
| 1980 | 4293.2 | 4510.7 |
| 1981 | 4638.9 | 4856.4 |
| 1982 | 4962.4 | 5179.9 |
| 1983 | 5304.8 | 5522.3 |
| 1983 | 5631.7 | 5849.2 |
| 1984 | 5970.5 | 6188.0 |
| 1985 | 6301.1 | 6518.6 |
| 1986 | 6636.0 | 6853.5 |
| 1987 | 6970.4 | 7187.9 |
| 1988 | 7301.5 | 7519.0 |
| 1989 | 7639.8 | 7857.3 |
| 1990 | 7967.2 | 8184.7 |
| 1991 | 8309.1 | 8526.6 |
| 1992 | 8633.1 | 8850.6 |
| 1993 | 8978.4 | 9195.9 |
| 1994 | 9299.3 | 9516.8 |
| 1994 | 9647.5 | 9865.0 |
| 1995 | 9965.9 | 10183.4 |
| 1996 | 10316.6 | 10534.1 |
| 1997 | 10632.9 | 10850.4 |
| 1998 | 10985.5 | 11203.0 |
| 1999 | 11300.2 | 11517.7 |

(e) Venus-Earth transfer

| Opposition calendar year | Departure date (Julian date minus $2.44\times10^6$) | Arrival date (Julian date minus $2.44\times10^6$) |
|---|---|---|
| 1980 | 4347.4 | 4493.5 |
| 1982 | 4932.5 | 5078.6 |
| 1983 | 5513.3 | 5659.4 |
| 1985 | 6101.0 | 6247.1 |
| 1986 | 6681.5 | 6827.6 |
| 1988 | 7267.1 | 7413.2 |
| 1990 | 7852.0 | 7998.1 |
| 1991 | 8432.9 | 8579.0 |
| 1993 | 9020.6 | 9166.7 |
| 1994 | 9601.1 | 9747.2 |
| 1996 | 10186.8 | 10332.9 |
| 1998 | 10771.6 | 10917.7 |
| 1999 | 11352.6 | 11498.7 |

(f) Mars-Earth transfer

| Opposition calendar year | Departure date (Julian date minus $2.44\times10^6$) | Arrival date (Julian date minus $2.44\times10^6$) |
|---|---|---|
| 1980 | 4132.9 | 4391.8 |
| 1982 | 4897.1 | 5156.0 |
| 1984 | 5669.1 | 5928.0 |
| 1986 | 6459.0 | 6717.9 |
| 1988 | 7269.9 | 7528.8 |
| 1990 | 8060.5 | 8319.4 |
| 1993 | 8832.6 | 9091.5 |
| 1995 | 9597.7 | 9856.6 |
| 1997 | 10362.0 | 10620.9 |
| 1999 | 11130.4 | 11389.3 |

TABLE VIII. - PREDICTED TRIP TIMES AND STAY TIMES FOR MINIMUM-TOTAL-PROPULSIVE-EFFORT ($\Sigma\Delta V$) TWO-PLANET STOPOVER TRAJECTORIES

(a) Earth-Mars-Venus-Earth

| Opposition year | Total propulsive effort, $\Sigma\Delta V$, km/sec | Total trip time, $T_t$, days | Stay time, days | | Ideal velocity increments, $\Delta V$, km/sec | Maneuver dates (Julian date minus $2.44\times10^6$) |
|---|---|---|---|---|---|---|
| | | | At Mars | At Venus | | |
| 1980 | 8.894 | 880.0 | 86.4 | 171.1 | 3.521, 0.817, 2.122, 1.819, 0.615, 0.0 | 4198.6, 4457.5, 4543.9, 4761.4, 4932.5, 5078.6 |
| 1982 | 8.894 | 1283.3 | 314.0 | 346.8 | 3.521, 0.817, 2.122, 1.819, 0.615, 0.0 | 4963.8, 5222.7, 5536.7, 5754.2, 6101.0, 6247.1 |
| 1984 | 8.894 | 1091.8 | 211.4 | 257.9 | 3.521, 0.817, 2.122, 1.819, 0.615, 0.0 | 5735.8, 5994.7, 6206.1, 6423.6, 6681.5, 6827.6 |

(b) Earth-Venus-Mars-Earth

| Opposition year | Total propulsive effort, $\Sigma\Delta V$, km/sec | Total trip time, $T_t$, days | At Mars | At Venus | Ideal velocity increments, $\Delta V$, km/sec | Maneuver dates (Julian date minus $2.44\times10^6$) |
|---|---|---|---|---|---|---|
| 1980 | 8.783 | 837.7 | 174.6 | 40.7 | 3.410, 0.615, 1.819, 2.122, 0.817, 0.0 | 4318.2, 4464.3, 4638.9, 4856.4, 4897.1, 5156.0 |
| 1982 | 8.783 | 1024.7 | 255.4 | 146.8 | 3.410, 0.615, 1.819, 2.122, 0.817, 0.0 | 4903.3, 5049.4, 5304.8, 5522.3, 5669.1, 5928.0 |
| 1983 | 8.783 | 1233.8 | 1.5 | 609.8 | 3.410, 0.615, 1.819, 2.122, 0.817, 0.0 | 5484.1, 5630.2, 5631.7, 5849.2, 6459.0, 6717.9 |
| 1985 | 8.783 | 1457.0 | 83.2 | 751.3 | 3.410, 0.615, 1.819, 2.122, 0.817, 0.0 | 6071.8, 6217.9, 6301.1, 6518.6, 7269.9, 7528.8 |

TABLE IX. - CHARACTERISTICS OF MINIMUM ENERGY, DOUBLE-STOPOVER TRAJECTORIES

(a) Earth-Mars-Venus-Earth

| Opposition year | Total propulsive effort, $\Sigma\Delta V$, km/sec | Total trip time, $T_t$, days | Stay time, days | | Ideal velocity increments, $\Delta V$, km/sec | Maneuver dates (Julian date minus $2.44\times10^6$) |
|---|---|---|---|---|---|---|
| | | | At Mars | At Venus | | |
| 1980 | 9.383 | 893.7 | 78.2 | 177.3 | 3.510, 0.811, 2.537, 1.558, 0.629, 0.0 | 4185.2, 4494.6, 4572.8, 4757.8, 4935.1, 5078.8 |
| 1982 | 9.253 | 1294.2 | 273.5 | 340.0 | 3.415, 1.020, 1.901, 1.942, 0.639, 0.0 | 4952.7, 5237.2, 5510.7, 5761.2, 6101.1, 6246.9 |
| 1984 | 9.341 | 1088.8 | 200.1 | 250.2 | 3.354, 1.184, 1.967, 1.899, 0.598, 0.0 | 5734.2, 5982.6, 6182.7, 6431.0, 6681.2, 6823.0 |
| (b) Earth-Venus-Mars-Earth | | | | | | |
| 1980 | 8.740 | 859.3 | 179.6 | 10.0 | 3.410, 0.615, 2.008, 1.798, 0.570, 0.0 | 4315.3, 4465.7, 4645.3, 4850.2, 4860.2, 5174.6 |
| 1982 | 8.701 | 1027.0 | 264.9 | 133.2 | 3.422, 0.601, 1.942, 1.901, 0.498, 0.0 | 4905.8, 5047.1, 5312.0, 5511.2, 5644.4, 5932.8 |
| 1983 | 9.019 | 1232.0 | 10.0 | 604.7 | 3.407, 0.715, 1.811, 2.137, 0.611, 0.0 | 5473.0, 5619.8, 5629.8, 5870.8, 6475.5, 6705.0 |
| 1985 | 9.323 | 1443.5 | 78.1 | 767.8 | 3.431, 0.593, 1.837, 2.057, 1.067, 0.0 | 6.072.7, 6218.2, 6296.3, 6541.5, 7309.4, 7516.2 |
| (c) Trajectories with reduced trip time | | | | | | |
| 1982 (Mars first) | 9.428 | 707.3 | 9.6 | 87.7 | 3.417, 1.026, 2.440, 1.613, 0.595, 0.0 | 4951.3, 5231.5, 5241.1, 5423.7, 5511.4, 5658.7 |
| 1983 (Venus first) | 10.565 | 633.1 | 9.7 | 10.3 | 3.410, 0.731, 1.830, 2.208, 2.048, 0.0 | 5472.4, 5618.9, 5629.2, 5856.3, 5866.0, 6105.4 |
| 1985 (Venus first) | 9.235 | 692.1 | 10.0 | 76.5 | 3.431, 0.594, 1.846, 2.100, 0.927, 0.0 | 6073.0, 6218.9, 6295.4, 6530.9, 6540.8, 6765.2 |

TABLE X. - INPUT DATA FOR VEHICLE MASS ESTIMATION

| | |
|---|---|
| Nuclear stages: | |
| Specific impulse, $I_{sp}$, sec | 800 |
| Engine specific thrust, $F/M_e g_\oplus$ | 4/1 |
| Propellant fraction, after-cooling, $M_{ac}/M_p$ | 0.05 |
| Tank structure fraction, $M_{ps}/M_p$ | 0.15 |
| Thrust structure fraction, $M_{fs} g_\oplus/F$ | 0.02 |
| Interstage structure fraction, $M_{is} g_\oplus/M_{pay} A_{max}$ | 0.02 |
| Auxiliary equipment fraction, $M_{aux}/M_{pay}$ | 0.01 |
| Vehicle initial acceleration, $A_o$, fraction of local gravity | 0.2 |
| Gravity and steering loss allowance (per ref. 16), percent of ideal $\Delta V$, typically | 9 |
| Launch-window and guidance corrections $\Delta V$ allowance, km/sec | 0.84 (total, for 6 main maneuvers plus 3 midcourses) |
| Chemical midcourse stages: | |
| Specific impulse, $I_{sp}$, sec | 425 |
| Engine specific thrust, $F/M_e g_\oplus$ | 10/1 |
| Tank structure fraction, $M_{ps}/M_p$ | 0.10 |
| Earth reentry vehicle: | |
| Mass, kg (lbm) | 6810 (15 000) |
| Entry speed capability, km/sec (ft/sec) | 15.5 (52 000) |
| Mission module and life support: | |
| Fixed mass, kg (lbm) | 34 100 (75 000) |
| Expendables, kg/day (lbm/day) | 22.78 (50) |
| Mission payloads: | |
| Mars excursion module, kg (lbm) | 40 000 (90 000) |
| Venus soft landing probe, kg (lbm) | 4540 (10 000) |
| Venus orbital experiments, kg (lbm) | 13 600 (30 000) |

TABLE XI. - COMPARISON BASED ON INITIAL MASS IN EARTH ORBIT OF DOUBLE STOPOVER AND VENUS-SWINGBY MISSIONS IN 1980 TO 1985

| Year | Type of trajectory | Total trip time, $T_t$, days | Initial mass in Earth orbit | |
|---|---|---|---|---|
| | | | kg | lbm |
| Double-stopover mode | | | | |
| 1980 | Earth-Mars-Venus-Earth | 867 | $530\times10^3$ | $1.17\times10^6$ |
| 1982 | Earth-Mars-Venus-Earth | 684 | 517 | 1.14 |
| 1983 | Earth-Venus-Mars-Earth | 632 | 640 | 1.41 |
| 1985 | Earth-Venus-Mars-Earth | 685 | 554 | 1.22 |
| Venus-swingby mode | | | | |
| 1980 | Outbound swingby | 663 | $485\times10^3$ | $1.02\times10^6$ |
| 1982 | Inbound swingby | 607 | 418 | .92 |
| 1984 | Inbound swingby | 538 | 454 | 1.00 |

TABLE XII. - CHARACTERISTICS OF INITIAL-MASS-OPTIMIZED TRAJECTORIES

| Trajectory | Year | Initial mass in Earth orbit, kg | Initial mass in Earth orbit, lbm | Trip time, $T_t$, days | Stay time, $T_s$, days | Earth reentry speed, km/sec | Minimum solar approach distance, AU | Ideal velocity increments, $\Delta V$, km/sec | Maneuver dates (Julian date minus $2.44\times10^6$) |
|---|---|---|---|---|---|---|---|---|---|
| Double stopovers of Mars and Venus | | | | | | | | | |
| Earth-Mars-Venus-Earth double stopover | 1980 | $5.28\times10^5$ | $1.17\times10^6$ | 867 | 79 (Mars) 174 (Venus) | 11.08 | 0.7197 | 3.51, 0.81, 2.54, 1.56, 0.651, 0.0 | 4187, 4494 4573, 4758, 4932, 5033 |
| | 1982 | $5.17\times10^5$ | $1.139\times10^6$ | 684 | 10 (Mars) 86 (Venus) | 11.12 | 0.7195 | 3.42, 1.03, 2.44, 1.61, 0.62, 0.0 | 4952, 5232, 5242, 5424, 5510, 5637 |
| Earth-Venus-Mars-Earth double stopover | 1983 | $6.37\times10^5$ | $1.405\times10^6$ | 632 | 10 (Mars) 10 (Venus) | 14.80 | 0.7216 | 3.40, 0.73, 1.82, 2.16, 2.12, 0.0 | 5476, 5619, 5629, 5861, 5871, 6108 |
| | 1985 | $5.54\times10^5$ | $1.22\times10^6$ | 685 | 10 (Mars) 77 (Venus) | 11.59 | 0.723 | 3.43, 0.59, 1.84, 2.07, 0.97, 0.0 | 6074, 6219, 6296, 6534, 6544, 6758 |
| Venus swingby and Mars stopover | | | | | | | | | |
| Outbound swingby | 1980 | $4.85\times10^5$ | $1.67\times10^6$ | 664 | 30 | 13.57 | 0.580 | 4.28, 0.0064, 2.24, 1.28 | 3842, [a]4003, 4170, 4200, 4505 |
| Inbound swingby | 1982 | $4.17\times10^5$ | $9.18\times10^5$ | 607 | 30 | 12.02 | 0.562 | 3.59, 1.27, 3.35, 0.0097 | 4933, 5211, 5241, [a]5390, 5540 |
| | 1984 | $5.08\times10^5$ | $1.12\times10^6$ | 538 | 30 | 12.32 | 0.650 | 3.88, 1.61, 4.06, 0.0032 | 5681, 5941, 5971, [a]6155, 6220 |
| Outbound swingby | 1986 | $4.52\times10^5$ | $9.97\times10^5$ | 601 | 30 | 11.59 | 0.631 | 3.92, 0.0113, 2.49, 1.11 | 6151, [a]6320, 6521, 6551, 6752 |

[a]Venus encounter.



NASA-Langley, 1970 —— 30 E-5291

*"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

# NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

*Details on the availability of these publications may be obtained from:*

**SCIENTIFIC AND TECHNICAL INFORMATION DIVISION**

**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

**Washington, D.C. 20546**